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Light sfermion interplay in the 125 GeV MSSM Higgs production and decay at the LHC

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ABSTRACT: We study the effects from light sfermions on the lightest Higgs boson production and decay at the Large Hadron Collider (LHC) within the Minimal Supersymmetric Standard Model (MSSM). We find that the scenario with light coloured sfermions — stops or sbottoms — has the potential to explain a non-universal alteration, as hinted by LHC data, of the gluon-gluon Fusion (μ_{ggF}) with respect to the Vector Boson Fusion (μ_{VBF}) event rates and, in particular, can predict $\frac{\mu_{VBF}}{\mu_{ggF}} > 1$ for all Higgs boson decay channels in large areas of the parameter space.

We also find that the scenario with a light stop/sbottom can be complemented by the scenario in which the total Higgs width, Γ_{tot} , is reduced due to a suppressed Yukawa coupling Y_b . In this case, the reduction of the Higgs production rates in the ggF process which occurs in the maximal mixing scenario is compensated by the reduction of the $H \rightarrow b\bar{b}$ partial decay width, the largest component of Γ_{tot} .

Furthermore, we highlight the fact that, in the light stop/sbottom scenario, event rates with the Higgs boson decaying to a $b\bar{b}$ final state are predicted to be essentially below unity, especially in case of ggF , which is doubly suppressed, at production, due to the negative interference from stop/sbottom loops, as well at decay level, due to the Y_b suppression. Therefore, during the future LHC runs, the measurement of $h \rightarrow b\bar{b}$ final states is a matter of special importance, which will offer additional handles to pin down the possible MSSM structure of the Higgs sector.

Amongst all viable MSSM configurations that we study (including revisiting a light stau solution), we emphasise most the scenario with a light stop, as the latter is also motivated by Dark Matter and Electro-Weak baryogenesis. We also perform fits of the MSSM against the LHC data for all scenarios which we introduce, emphasising the fact that in most cases these are better than for the SM.

KEYWORDS: Supersymmetry Phenomenology

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1 Introduction

The 4th of July 2012 was an important date for the particle physics community, when the discovery of a Higgs boson with a mass of 125 GeV was announced by the ATLAS and CMS collaborations [1, 2]. This event was dramatic since a Higgs boson was the last undiscovered particle desperately searched for to complete the experimental verification of the Standard Model (SM). At the same time, the detection of this new state has opened a new chapter in the exploration of Beyond the SM (BSM) physics, since many BSM models are consistent with the properties of the discovered Higgs boson within the accuracy of the experimental data (some are even more preferred by data in comparison to the SM). Furthermore, there still remains the need to surpass the SM from the theoretical side, as the discovered object does nothing to remedy its fundamental flaws: the hierarchy, naturalness and/or fine-tuning problems, the absence of gauge coupling unification at any scale, etc. Also, the SM does not address fundamental experimental problems on the cosmological scale, such as Dark Matter (DM)/Dark Energy and Electro-Weak (EW) Baryo-Genesis (EWBG).

The recent post-Moriond analysis of Higgs boson properties reported by ATLAS [3] and CMS [4] are based on 4.7 fb^{-1} at 7 TeV and $13\text{--}20.7 \text{ fb}^{-1}$ at 8 TeV of data (ATLAS) and 5.1 fb^{-1} at 7 TeV and 19.6 fb^{-1} at 8 TeV of data (CMS). The results are presented for various Higgs boson production and decay channels. The production modes include gluon-gluon Fusion (ggF), Vector Boson Fusion (VBF), Higgs-strahlung (VH) and associated

production with top-quarks (ttH) while the studied decay modes include $h \rightarrow \gamma\gamma$, ZZ , WW , $\tau^+\tau^-$ and $b\bar{b}$.¹

The magnitude of the signal is usually expressed via the “signal strength” parameters μ , defined for either the entire combination of or the individual decay/production modes, relative to the SM. In our study we define individual μ_{XY} for a given production (X) and decay (Y) channel, in terms of production cross sections σ and decays widths Γ (in preference to Branching Ratios (BRs)):

$$\mu_{X,Y} = \frac{\sigma_X^{\text{MSSM}}}{\sigma_X^{\text{SM}}} \times \frac{\text{BR}_Y^{\text{MSSM}}}{\text{BR}_Y^{\text{SM}}} = \kappa_X \times \frac{\Gamma_Y^{\text{MSSM}}/\Gamma_{\text{tot}}^{\text{MSSM}}}{\Gamma_Y^{\text{SM}}/\Gamma_{\text{tot}}^{\text{SM}}} = \kappa_X \times \frac{\Gamma_Y^{\text{MSSM}}}{\Gamma_Y^{\text{SM}}} \times \frac{\Gamma_{\text{tot}}^{\text{SM}}}{\Gamma_{\text{tot}}^{\text{MSSM}}} = \kappa_X \times \kappa_Y \times \kappa_h^{-1}, \quad (1.1)$$

where, generally, $X = ggF, \text{VBF}, \text{VH}, ttH$ and $Y = \gamma\gamma, WW, ZZ, b\bar{b}, \tau\bar{\tau}$, etc. Notice that, in the above equations, κ_X and κ_Y are equal to the respective ratios of the couplings squared while κ_h is the ratio of the total Higgs boson width in the MSSM relative to the SM. For example, for $gg \rightarrow h \rightarrow \gamma\gamma$, we have

$$\mu_{X,Y} \equiv \mu_{ggF,\gamma\gamma} = \kappa_{ggF} \times \kappa_{\gamma\gamma} \times \kappa_h^{-1} = \frac{\sigma_{ggF}^{\text{MSSM}}}{\sigma_{ggF}^{\text{SM}}} \times \frac{\Gamma_{h^{\text{MSSM}}\gamma\gamma}}{\Gamma_{h^{\text{SM}}\gamma\gamma}} \times \kappa_h^{-1}. \quad (1.2)$$

Notice that the combination of individual production and decay channels which has been done by experimental papers is a non-trivial procedure which takes into account the efficiency of the various channels determining in turn the corresponding weights in the overall combination.

The respective results as reported by ATLAS are given by [3]

$$\mu(h \rightarrow \gamma\gamma) = 1.6 \pm 0.3 \quad (1.3)$$

$$\mu(h \rightarrow ZZ^{(*)}) = 1.5 \pm 0.4 \quad (1.4)$$

$$\mu(h \rightarrow WW^{(*)}) = 1.0 \pm 0.3 \quad (1.5)$$

$$\mu(h \rightarrow b\bar{b}) = -0.4 \pm 1.0 \quad (1.6)$$

$$\mu(h \rightarrow \tau\bar{\tau}) = 0.8 \pm 0.7 \quad (1.7)$$

while from the CMS collaboration one has [4]

$$\mu(h \rightarrow \gamma\gamma) = 0.77 \pm 0.27 \quad (1.8)$$

$$\mu(h \rightarrow ZZ) = 0.92 \pm 0.28 \quad (1.9)$$

$$\mu(h \rightarrow WW) = 0.68 \pm 0.20 \quad (1.10)$$

$$\mu(h \rightarrow b\bar{b}) = 1.15 \pm 0.62 \quad (1.11)$$

$$\mu(h \rightarrow \tau\bar{\tau}) = 1.10 \pm 0.41. \quad (1.12)$$

It is not possible to perform this combination accurately in this phenomenological study as for this one needs to know all details on various experimental efficiencies for all production and decay channels which are not publicly available. Moreover, the overall

¹Sensitivity to the $h \rightarrow Z\gamma$ mode is much less in comparison, though some limits already exist [5]. Similarly, for Higgs boson invisible decays [6].

Figure 1. Likelihood contours and best fit values in the $(\mu_{\text{VBF+VH}}, \mu_{\text{ggF+ttH}})$ plane for different decay channels observed at the LHC: (a) ATLAS results [3] with 68% (solid lines) and 95% (dashed lines) CL contours and SM expectation (+ symbol); (b) CMS results [4] with 68% (solid line) CL contours and SM expected value ($\diamond$ symbol). (Herein, the label ggH corresponds to our ggF .)

signal strength μ for all production channels combined does not carry valuable information about possible new physics since in most BSM scenarios the main production channels ggF and VBF are non-universally altered in comparison to the SM.

Luckily, both experiments have produced results for the $\mu_{X,Y}$ parameters for ggF and VBF separately, as presented in figure 1. Herein, such results for both collaborations are visualised as likelihood contours in terms of Confidence Level (CL) rates for the different final states mentioned above.

One can see that these results, on the one hand, are consistent with the SM model at 95% CL while, on the other hand, there is still a lot of room to accommodate deviations from the SM, at least in the $\pm 40\%$ range at 95% CL. One should also notice that for the $h \rightarrow \gamma\gamma$ measurement, the ATLAS result is about 2σ above the SM prediction for both ggF and VBF production processes, while the CMS result is approximately 1σ below the SM value for ggF and about 1σ above the SM for VBF, respectively. Thus, one can also see that there is some tension between the ATLAS and CMS results. From figure 1 one can nonetheless see the interesting general pattern (still within the $1-2\sigma$ error interval) that $\mu_{\text{VBF},\gamma\gamma}$ is actually bigger than $\mu_{\text{ggF},\gamma\gamma}$ for both ATLAS and CMS, noting that for the CMS collaboration $\mu_{\text{ggF},\gamma\gamma}$ is essentially below one.² This trend has been quantified by the ATLAS collaboration, who have produced a best fit value of [7]

$$\frac{\mu_{\text{VBF}}}{\mu_{\text{ggF+ttH}}} = 1.4^{+0.4}_{-0.3}(\text{stat})^{+0.6}_{-0.4}(\text{sys}) \quad (1.13)$$

for a combination of the $\gamma\gamma$, ZZ and WW data.

²One should also mention that, initially, both collaborations had initially observed a generic enhancement in the $h \rightarrow \gamma\gamma$ channel while, later on, the CMS results have shifted towards the SM value or even below.

On the basis of the pattern of measured $\mu_{X,Y}$, it is clear that BSM solutions to the LHC data ought to be investigated thoroughly. Herein, in particular, we discuss the case of the Minimal Supersymmetric Standard Model (MSSM), assess how genuine Supersymmetry (SUSY) effects can affect the Higgs production or decay dynamics (or indeed both) and draw a picture of the preferred SUSY parameter space in the light of the Higgs LHC data.

In our analysis, we concentrate on the VBF and ggF productions channels only, which are the leading ones, and limit the study of the decay signatures to the cases of $h \rightarrow \gamma\gamma, WW, ZZ$ final states, as these are the production and decay modes with the most accurate experimental results. We should also remark that we carried out our investigation using renormalisation-group-improved diagrammatic calculations, including higher-order logarithmic and threshold corrections, using CPsuperH [8, 9] (version 2.3).

Quite apart from the fact that current data shows a tendency for $\mu_{\text{VBF},YY} > \mu_{\text{ggF},YY}$, the LHC measurements also point to a rather light Higgs mass. While the possibility that the SM Higgs state had such a mass would be merely a coincidence (as its mass is a free parameter), in the MSSM, in contrast, the mass of the lightest Higgs boson with SM-like behaviour is naturally confined to be ≤ 135 GeV [10, 11] by SUSY itself, which in essence relates trilinear Higgs and gauge couplings, so that the former are of the same size as the latter, in turn implying such a naturally small Higgs mass value. Therefore, to some extent, the Higgs boson mass which is measured at the LHC favours the MSSM (or some other low energy SUSY realisation) over the SM, so that it is of the utmost importance to test the validity of this SUSY hypothesis against the LHC Higgs data and to establish the viable parameter space.

As we know, the MSSM Higgs sector consists of five Higgs bosons: two CP-even neutral bosons, h, H (with masses such that $m_h < m_H$),³ one CP-odd, A , and a pair which is charged, $H^\pm$. At tree level, the mixing between the two CP-even neutral Higgs bosons is defined by the mixing angle α , which is a derived quantity uniquely determined by two independent parameters which can be taken as the mass of any of the five physical states (hereafter we take m_h) and the ratio between the Vacuum Expectation Values (VEVs) of the two Higgs doublet fields pertaining to the MSSM, denoted by $\tan\beta$. However, while performing an analysis in higher orders (or in the presence of loop diagrams at lowest order as is the case for the hgg , $h\gamma\gamma$ and $h\gamma Z$ effective couplings), one ought to account for the sparticle sector of the MSSM too, which in turn implies the introduction of additional parameters.

Previous literature has explored the Higgs sector in a variety of SUSY scenarios, such as the MSSM [12–31] (also the constrained version [32–38]), Next-to-MSSM [39–46] and (B-L)SSM [47–50], including scenarios with light charginos [51], staus [20, 52] and stops [20].

In our paper we re-examine the light stop, sbottom and stau scenarios, but also extend previous research by allowing any combination of MSSM quantum corrections, mixing effects and/or light MSSM fermions entering loops. In particular, we are the first to discuss how the MSSM could explain a non-universal alteration in $\mu_{\text{VBF},YY}$ versus $\mu_{\text{ggF},YY}$

³We have deliberately used so far the symbol h to signify both the SM Higgs state and the lightest MSSM CP-even one, as our MSSM solutions to the Higgs data will only involve the latter amongst the possible neutral Higgs states.

from their SM values such that $\frac{\mu_{\text{VBF}}}{\mu_{ggF}} \neq 1$, and use these to examine the compatibility of the MSSM against LHC data. We also examine its ability to produce enhanced (with respect to the SM) rates in the di-photon channel, such that $\mu_{\text{VBF}} > 1$ and/or $\mu_{ggF} > 1$ and explore the effects of deviations entering all other measured Higgs boson couplings to SM particles.

The plan of the paper is as follows. In section 2 we introduce the general setup and the MSSM parameter space that we explore, specific to the Higgs sector. In section 3.1 we study the possible generic MSSM effects on the relevant dynamics, namely, onto Higgs production, decay and total width. In sections 3.2 and 3.3 we study the effects of stops and sbottoms, respectively, where we find that both can give rise to non-universal alterations in μ_{VBF} versus μ_{ggF} as both particles are able to affect the ggF fusion rate but not the VBF one. Section 3.4 explores the stau contribution, where we find that it can only produce a universal increase in cross section in the di-photon channel, irrespectively of the production channel, as it only appears in the $\gamma\gamma$ (and $Z\gamma$) decay loops. In view of the Higgs data potentially indicating a non-universality in the production channels compared to SM predictions, in section 3.5 we look at the combined effects of these scenarios as well as perform a χ^2 fit of the MSSM parameter space with respect to LHC data. We draw our conclusions in section 4.

2 MSSM setup and the parameter space

The MSSM is essentially a straightforward supersymmetrisation of the SM with the minimal number of new parameters. It is the most widely studied potentially realistic SUSY model. Furthermore, while different assumptions about the SUSY breaking dynamics can be made and these in turn lead to quite different phenomenological predictions, one can always assume an EW scale configuration and scan over the SUSY parameters relevant at that energy.

From this point of view, it becomes important to specify the MSSM spectrum (of masses and couplings). The particle content of the MSSM is three generations of (chiral) quark and lepton superfields, the (vector) superfields necessary to gauge the $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$ group of the SM and two (chiral) $\text{SU}(2)$ Higgs doublet superfields. The introduction of a second Higgs doublet, with respect to the SM, is necessary in order to cancel the anomalies produced by the fermionic members of the first Higgs superfield and also to give masses to both up- and down-type fermions.

The interactions between Higgs and matter superfields are described by the superpotential

$$W = Y_{ij}^E L_i E_j^c H_d + Y_{ij}^D Q_i D_j^c H_d + Y_{ij}^U Q_i U_j^c H_u + \mu H_u H_d. \quad (2.1)$$

Here Q_L contains the $\text{SU}(2)$ (s)quark doublets and U_L^c and D_L^c the corresponding singlets, while the (s)lepton doublets and singlets reside in L_L and E_L^c , respectively. In addition, H_u and H_d denote Higgs superfields with hypercharge $Y = \pm \frac{1}{2}$. The MSSM assumes certain soft SUSY breaking terms at a grand unification scale $M_{\text{GUT}} = 3 \times 10^{16} \text{ GeV}$. These soft SUSY breaking terms are categorised as trilinear scalar couplings A_{ij}^f , gaugino masses M_a , sfermion mass-squared terms $\tilde{m}_{ij}^f$, and bilinear scalar coupling B .

In the MSSM, the SM-like Higgs is the lightest CP-even Higgs, which is defined as

$$h = \sin \alpha \operatorname{Re}(H_d^0) + \cos \alpha \operatorname{Re}(H_u^0),$$

with mixing angle α given by

$$\tan 2\alpha = \tan 2\beta \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}. \quad (2.2)$$

The mass of the MSSM Higgs can be written, at one loop, as [53–55]

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[\log \left(\frac{M_S^2}{m_t^2} \right) + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t}{12M_S^2} \right) \right], \quad (2.3)$$

where $M_S^2 = \frac{1}{2}(M_{t_1}^2 + M_{t_2}^2)$ and $X_t = A_t - \mu \cot \beta$. From this expression, one can easily show that the maximum value of m_h is obtained at the maximal stop mixing, i.e., at $X_t = \sqrt{6}M_S$. Also, in order to have $m_h = 125$ GeV, one should assume that at least one stop has a mass of $\mathcal{O}(1)$ TeV, while the other stop can be light. In addition, a quite large stop mixing is required, i.e., $A_t \gtrsim 1$ TeV.

In our analysis we are interested in the stop, sbottom and stau states as light particles. In general, one can write the squared mass matrices of these particles in the basis of the gauge eigenstates $(\tilde{f}_L, \tilde{f}_R)$ as

$$M_{\tilde{f}}^2 = \begin{pmatrix} m_f^2 + m_{LL}^2 & m_f X_f \\ m_f X_f & m_f^2 + m_{RR}^2 \end{pmatrix}, \quad (2.4)$$

where

$$m_{LL}^2 = m_{\tilde{f}_L}^2 + (T_{3f} - Q_f s_W^2) M_Z^2 \cos 2\beta, \quad (2.5)$$

$$m_{RR}^2 = m_{\tilde{f}_R}^2 + Q_f s_W^2 M_Z^2 \cos 2\beta, \quad (2.6)$$

$$X_f = A_f - \mu (\tan \beta)^{-2T_{3f}}, \quad (2.7)$$

where T_{3f} is the third component of the weak isospin and Q_f is the electric charge. Thus, the sfermion physical masses are given by

$$m_{\tilde{f}_{1,2}}^2 = m_f^2 + \frac{1}{2} \left[m_{LL}^2 + m_{RR}^2 \mp \sqrt{(m_{LL}^2 - m_{RR}^2)^2 + 4m_f^2 X_f^2} \right], \quad (2.8)$$

and the mixing angles are given by

$$\tan 2\theta_f = \frac{2m_f X_f}{m_{LL}^2 - m_{RR}^2}. \quad (2.9)$$

In this regard, one notices that the mixing in the stop sector is very strong, hence one of the stops, $\tilde{t}_1$, can be very light. Also, with large $\tan \beta$ and $|\mu|$, the mixing in the sbottom and stau sectors can also be very strong, therefore light $\tilde{b}_1$ and $\tilde{\tau}_1$ are further obtained.

LHC constraints on SUSY masses are generally quoted as around 600–700 GeV for stops and sbottoms and in the region of 300 GeV for staus [3, 4], depending on assumptions

Parameter	Range	Parameter	Range
$\tan \beta$	[2, 50]	M_{Q3}	[0.1, 10] TeV
$M_{H^\pm}$	[0.2, 2] TeV	M_{U3}	[0.1, 5] TeV
μ	[0.1, 5] TeV	M_{D3}	[0.1, 20] TeV
A_t	[0.1, 10] TeV	M_{L3}	[0.1, 5] TeV
A_b	[0.1, 10] TeV	M_{E3}	[0.1, 5] TeV
A_τ	[0.1, 5] TeV	M_3	[0.1, 5] TeV
$A_e, A_\mu, A_u, A_d, A_c, A_s$	fixed at 10 GeV	M_2	fixed at 3 TeV

Table 1. Range of scanned parameters. M_1 can be chosen to provide an LSP (neutralino) mass to overcome cosmological and LHC constraints without altering any other relevant results.

regarding the decay processes and the masses of decay products. However, these results all rely strongly on a sizeable mass splitting between these sparticles and the Lightest Supersymmetric Sparticle (LSP), a neutralino, to which they decay. These limits are drastically reduced in the region of low mass splittings: e.g., if $m_{\tilde{t}} \approx m_t + m_{\tilde{\chi}^0}$, then the stop signal becomes difficult to distinguish from the $t\bar{t}$ background and the LHC data are unable to constrain the stop mass. A similar situation arises for other mass splitting scenarios, such as when the stop mass is close to the mass of the LSP $m_{\tilde{t}} \approx m_c + m_{\tilde{\chi}^0}$. In this case the stop mass limit is reduced down to the LEP limit ~ 95 GeV [56]. The limits for sbottom and stau masses can also be markedly reduced down to LEP limits (~ 95 GeV for sbottoms and ~ 85 GeV for staus [56]) for appropriate mass splittings.

In the present study, we performed a large scan of parameter space using CPsuperH to produce the data points, concentrating on those parameters with an important role in the masses and couplings of the stops, sbottoms and staus as well as the mass of the Higgs boson and its couplings to the bottom quark.⁴ These masses and couplings are largely independent of the M_1 mass parameter (they vary only $\sim 0.1\%$ for M_1 ranged from 0.1 TeV–100 TeV). However when $M_1 \ll (M_2, \mu)$, the lightest neutralino mass, $m_{\tilde{\chi}_1^0} \approx M_1$, so that for any point in our parameter scan its values can be chosen to give whichever LSP mass is required to be consistent with cosmological and LHC constraints, without otherwise altering our conclusions. In table 1, we list the range of parameters of this scan.

To increase the number of points in the parameter space of interest, three further localised scans were performed, in each case reducing the scanned range of one variable, with the other variable ranges remaining as described in table 1. The altered ranges in these additional scans were:

1. $100 \text{ GeV} \leq M_{U3} \leq 300 \text{ GeV}$ to produce light stops;
2. $100 \text{ GeV} \leq M_{D3} \leq 400 \text{ GeV}$ to produce light sbottoms;
3. $100 \text{ GeV} \leq M_{E3} \leq 400 \text{ GeV}$ and $100 \text{ GeV} \leq M_{L3} \leq 400 \text{ GeV}$ to produce light staus.

⁴Recall, in fact, that the dominant component of the Higgs boson width for masses of order 125 GeV is typically the partial width in $b\bar{b}$ pairs.

In order to avoid colour breaking minima of the $\tilde{t}$ or $\tilde{b}$ fields, we apply the $|A_t|, |\mu| \leq 1.5(M_{Q3} + M_{U3})$ constraints to all plots and numerical results unless otherwise stated [57–59]. These requirements are somewhat conservative, in the light of a very recent analysis in ref. [60], yet we maintained them in order to simplify our study.

3 MSSM effects in Higgs production and decay

In this section, we discuss MSSM effects which alter the Higgs event rates at the LHC as compared to those of the SM. We start with a first subsection, in turn divided in the three parts corresponding to introducing the structure of Higgs cross sections, di-photon decay and total width. The remaining four subsections deal with stop, sbottom, stau and their combined effects, respectively, in either of these contexts.

3.1 The three contexts for MSSM effects

3.1.1 MSSM Higgs production

We start our discussion with MSSM Higgs boson production via the gluon-gluon fusion process, which is the dominant channel for Higgs searches at the LHC. In the SM, this mode is predominantly mediated by top quarks via a one-loop triangle diagram while the contribution from other quarks, even the bottom one, is only at the few percent level.

In the MSSM, however, strongly interacting superpartners of the SM quarks, i.e., the squarks, could provide a sizeable contribution to this triangle loop.

The lowest order parton-level cross section can be written as

$$\hat{\sigma}_{\text{LO}}(gg \rightarrow h) = \frac{\pi^2}{8m_h} \Gamma_{\text{LO}}(h \rightarrow gg) \Delta(\hat{s} - m_h^2), \quad (3.1)$$

where $\hat{s}$ is the center-of-mass energy at the partonic level and $\Delta(\hat{s} - m_h^2)$ is the Breit-Wigner form of the Higgs boson propagator, which is given by

$$\Delta(\hat{s} - m_h^2) = \frac{1}{\pi} \frac{\hat{s} \Gamma_h / m_h}{(\hat{s} - m_h^2)^2 + (\hat{s} \Gamma_h / m_h)^2},$$

and Γ_h is the total Higgs boson decay width, while its partial decay width, $\Gamma_{\text{LO}}(h \rightarrow gg)$, is given by

$$\Gamma_{\text{LO}}(h \rightarrow gg) = \frac{\alpha_s^2 m_h^3}{512\pi^3} \left| \sum_f \frac{2Y_f}{m_f} F_{1/2}(x_f) + \sum_S \frac{g_{hSS}}{m_S^2} F_0(x_S) \right|^2, \quad (3.2)$$

where Y_f and g_{hSS} are the MSSM Higgs couplings to the respective (s)particle species for fermion (spin-1/2) and scalar (spin-0) particles, respectively, entering the triangle diagram. The loop functions $F_{1/2,0}$ can be found, for example, in [19]. Here, x_i is defined as $4m_i^2/m_h^2$, with m_i being the mass running in the loop. In the decoupling (or quasi-decoupling) regime, as in the case of the SM limit of the MSSM, the top quark contribution is dominant among the quarks, since it has the largest Yukawa coupling, while the contribution from the other quarks (mainly coming from the bottom quark) is at the percent level, as intimated.

The role of the bottom quark can be dramatically different though in the non-decoupling regime, when the hbb Yukawa coupling, $Y_b^{\text{MSSM}} = -\frac{m_b \sin \alpha}{v \cos \beta} = Y_b^{\text{SM}} \frac{\sin \alpha}{\cos \beta}$ is enhanced by $\sin \alpha / \cos \beta \simeq \tan \beta$ in comparison to the SM, enabling the bottom quark contribution to the triangle loop to increase and even dominate over the top quark for large values of $\tan \beta$. However, this is not a realistic possibility, since LHC data do not indicate such significant deviations of the Higgs couplings from SM the values (they are within a 50% or so range from the latter), while data on the Higgs mass measurement indicate that, if the MSSM is realised in Nature, then the decoupling or quasi-decoupling regime should take place. In fact, the Higgs boson mass is close to the one reached in the decoupling limit, requiring $\alpha \approx \beta - \frac{\pi}{2}$, hence $Y_b^{\text{MSSM}} \approx Y_b^{\text{SM}}$ as well as $Y_t^{\text{MSSM}} \equiv \frac{m_t \cos \alpha}{v \sin \beta} \approx Y_t^{\text{SM}}$.

From eq. (3.2) one can see that the g_{hSS} coupling has dimension one, while it is more convenient to define a dimensionless $\hat{g}_{hSS}$ to be used hereafter:

$$\hat{g}_{hSS} = \frac{g_{hSS}}{M_W/g} = \frac{g_{hSS}}{(4\sqrt{2}G_F)^{-\frac{1}{2}}} = g_{hSS} \sqrt{4\sqrt{2}G_F}, \quad (3.3)$$

where G_F is the Fermi constant. So $\Gamma_{\text{LO}}(h \rightarrow gg)$ will have a form

$$\Gamma_{\text{LO}}(h \rightarrow gg) = \frac{\alpha_s^2 m_h^3}{512\pi^3} \left| \sum_f \frac{2Y_f}{m_f} F_{1/2}(x_f) + \sum_S \frac{\hat{g}_{hSS}}{m_S^2} \frac{M_W}{g} F_0(x_S) \right|^2. \quad (3.4)$$

One should also note that the functions $F_{1/2}(x)$ and $F_0(x)$ reach a plateau very quickly for $x > 1$ and their values are about 1.4 and 0.4, respectively. This fact has important consequences, which we will discuss together with the Higgs decay into two photons, in the next subsection. The specific effects of stop and sbottom loops will be discussed in sections 3.2 and 3.3.

3.1.2 MSSM Higgs decay into di-photons

In the SM, the one-loop partial decay width of the h state into two photons is given by [61, 62]

$$\begin{aligned} \Gamma(h \rightarrow \gamma\gamma) &= \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left| F_1(x_V) + \sum_f N_{c,f} Q_f^2 F_{1/2}(x_f) \right|^2 \\ &= \frac{\alpha^2 m_h^3}{1024\pi^3} \frac{g^2}{M_W^2} \left| F_1(x_V) + \sum_f N_{c,f} Q_f^2 F_{1/2}(x_f) \right|^2 \\ &= \frac{\alpha^2 m_h^3}{1024\pi^3} \left| \frac{g_{hWW}}{M_W^2} F_1(x_V) + \sum_f \frac{2Y_f}{m_f} N_{c,f} Q_f^2 F_{1/2}(x_f) \right|^2 \end{aligned} \quad (3.5)$$

while in the MSSM the one-loop partial decay width of the h state into two photons also gets a contribution from scalar particles represented by sfermions and charged Higgs boson and is given by

$$\begin{aligned} \Gamma(h \rightarrow \gamma\gamma) &= \\ &= \frac{\alpha^2 m_h^3}{1024\pi^3} \left| \frac{g_{hWW}}{M_W^2} F_1(x_V) + \sum_f \frac{2Y_f}{m_f} N_{c,f} Q_f^2 F_{1/2}(x_f) + \sum_S \frac{\hat{g}_{hSS}}{m_S^2} \frac{M_W}{g} N_{c,S} Q_S^2 F_0(x_S) \right|^2, \end{aligned} \quad (3.6)$$

where V, f , and S stand for Vector, fermion and scalar particles respectively, entering the one-loop triangle diagram, g_{hWW} is the MSSM Higgs coupling to W -boson, while Y_f and $\hat{g}_{hSS}$ are the MSSM couplings of Higgs boson to fermions and scalars defined in the previous subsection.

The genuine SUSY contributions to $\Gamma(h \rightarrow \gamma\gamma)$ are mediated by charged Higgs, charginos and charged sfermions. The SM-like part is dominated by W -gauge bosons, for which $F_1(x_W) \simeq -8.3$, whereas the top quark loop is subdominant and enters with opposite sign, $N_{c,f} Q_f^2 F_{1/2}(x_f) \simeq 1.8$, with all other fermions contributing negligibly. It is also worth mentioning that $F_0(x_S) \sim 0.4$, which is about a factor 20 smaller than $F_1(x_W)$ and approximately a factor 4 smaller than $F_{1/2}(x_f)$.

Keeping this in mind, let us discuss possible sources of the enhancement of the $h \rightarrow \gamma\gamma$ effective coupling which in the MSSM may come through one of the following possibilities: (a) by the induction of a large scalar contribution, due to the light stop or/and sbottom or/and stau, with negative coupling $\hat{g}_{hSS}$ so that it interferes constructively with the dominant W -contribution; (b) via charged Higgs boson contributions; (c) via chargino contributions; (d) via modification of the Yukawa couplings of top and bottom quarks in the loop. In the decoupling or quasi-decoupling regimes which eventually take place, as discussed above, scenario (d) does not occur. As for case (b), then taking into account that the charged Higgs mass is limited to be above 200 GeV (see e.g. [31, 63] and references therein), the fact that its loop contribution is suppressed by a factor of $(M_W/M_{H^\pm})^2$ and that $\hat{g}_{hH^+H^-}$ is of the order of the electroweak coupling (contrary to the $\hat{g}_{hSS}$ coupling for squarks and sleptons which can be large as we discuss below), we have found that the contribution from charged Higgs bosons is generally negligible. In case (c), the chargino contribution can be bigger than that of the charged Higgs, because of the ratio $F_{1/2} : F_0 \simeq 4$ and because the chargino has a lower mass limit of approximately 100 GeV (coming from LEP2 [64]). We have found that the maximum chargino contribution is reached in the $\mu \rightarrow M_2, \tan\beta \rightarrow 1$ limit (where μ is the Higgs mass parameter while M_2 is the gaugino soft breaking mass) and can enhance the SM $h \rightarrow \gamma\gamma$ partial decay width by about 30%. This agrees with the recent results of [51]. The scenario with very light charginos is not the focus of our paper, where we assume charginos to have a mass of at least a few hundred GeVs, and for which the virtual chargino contribution to the $h \rightarrow \gamma\gamma$ decay is negligible. Moreover, the effect from the light charginos which could alter only the $h \rightarrow \gamma\gamma$ decay is qualitatively similar to the effect from the light staus, which quantitatively can be much larger [52], and which we consider in the current study in great detail together with the light sbottom and light stop scenarios. Therefore, in this study we concentrate on scenario (a) in which sizeable MSSM contributions via scalar loops are still possible.

It is worth stressing again two important details related to the scalar contribution to $h \rightarrow \gamma\gamma$. Firstly, the smallness of the loop function F_0 with respect to $F_{1/2}$ and with respect to F_1 too, and, secondly, the mass suppression factor, $(M_W/M_S)^2$, mentioned above. Therefore the only way to have a sizeable effect from the scalar loops is to be in a scenario with large coupling $\hat{g}_{hSS}$ and light scalars. In such a scenario the scalar loop competing with the fermion loop has a larger relative contribution to $\Gamma(h \rightarrow gg)$ than to $\Gamma(h \rightarrow \gamma\gamma)$ where it would also compete with the dominant vector boson loop. At the same time, the

contribution from squarks is opposite for Higgs production via gluon-gluon fusion compared to di-photon decay: depending on the sign of $\hat{g}_{hSS}$, they will destructively (constructively) interfere with top quarks in production loops and constructively (destructively) interfere with W -boson loops in Higgs boson decays. Therefore, any squark loop which causes an increase (decrease) in $\Gamma(h \rightarrow \gamma\gamma)$ will cause a proportionally larger decrease (increase) in $\Gamma(h \rightarrow gg)$.

3.1.3 MSSM Higgs total decay width

The total Higgs decay width in the MSSM is given, similarly to the SM, by the sum of all the Higgs partial decay widths, i.e., $\Gamma_{\text{tot}} = \Gamma_{b\bar{b}} + \Gamma_{WW} + \Gamma_{ZZ} + \Gamma_{\tau\bar{\tau}}$. Other partial decay widths into SM particles are much smaller and can safely be neglected. As per decays into SUSY states, we assume that the lightest neutralino is heavy enough, so we do not have invisible decay channels with large rates. In the SM with a 125 GeV Higgs mass, these partial decay widths are given by $\Gamma_{b\bar{b}} = 2.4 \times 10^{-3}$ GeV, $\Gamma_{WW} = 8.8 \times 10^{-4}$ GeV, $\Gamma_{ZZ} = 1.0 \times 10^{-4}$ GeV and $\Gamma_{\tau\bar{\tau}} = 2.4 \times 10^{-4}$ GeV.

In the MSSM, when $m_h \approx 125$ GeV, this width is dominated by the partial width to $b\bar{b}$, $\Gamma(h \rightarrow b\bar{b})$, which is controlled by the bottom quark Yukawa coupling, Y_b . In the SM, it is given by the expression $Y_b \equiv g_{hb\bar{b}} = m_b/v$.

At large $\tan \beta$, sbottom-gluino and stop-chargino loops give corrections to this Yukawa, which can be approximated by [65]

$$Y_b \approx -\frac{m_b \sin \alpha}{\cos \beta (1 + \Delta m_b) v} \left(1 - \frac{\Delta m_b}{\tan \alpha \tan \beta} \right) \quad (3.7)$$

where

$$\Delta m_b = \frac{2\alpha_3}{3\pi} m_g \mu \tan \beta I(m_{b_1}^2, m_{b_2}^2, |m_{\tilde{g}}|^2) + \frac{|h_t|^2}{16\pi^2} A_t \mu \tan \beta I(m_{t_1}^2, m_{t_2}^2, |\mu|^2) \quad (3.8)$$

and

$$h_t = \frac{m_t}{v \sin \beta} \quad (3.9)$$

with α_3 , $m_{\tilde{g}}$ and A_t being the SUSY-QCD constant, gluino mass and top quark trilinear parameter, respectively, and where the loop function $I(a, b, c)$ is defined as

$$I(a, b, c) = \frac{ab \ln(a/b) + bc \ln(b/c) + ca \ln(c/a)}{(a-b)(b-c)(a-c)}. \quad (3.10)$$

$I(a, b, c)$ is a positive definite function, therefore with positive m_g , μ and A_t , the correction Δm_b is positive, and Y_b is reduced. In particular, we see that this correction is large for large values of μ .

As the total width of the Higgs is dominated by the partial width to $b\bar{b}$, a reduction in Y_b will lead to a reduction in both $\Gamma(h \rightarrow b\bar{b})$ and Γ_{tot} , with a subsequent universal increase in all other BRs and $\mu_{X,Y} = \kappa_X \times \kappa_Y \times \frac{\Gamma_{\text{tot}}^{\text{SM}}}{\Gamma_{\text{tot}}^{\text{MSSM}}}$ irrespectively of the production channel.

However, in the decoupling limit $M_A \gg M_Z$, $\tan \alpha \rightarrow -\cot \beta$, therefore

$$\left(1 - \frac{\Delta m_b}{\tan \alpha \tan \beta} \right) \rightarrow (1 + \Delta m_b) \quad (3.11)$$

which along with $\frac{\sin \alpha}{\cos \beta} \rightarrow -1$ means that Y_b reduces to its SM value.

Figure 2. Results of the scan for $\kappa_{b\bar{b}}$ in the (M_A, μ) (left) and $(A_t, \tan \beta)$ (right) planes, respectively, where we have required $124 \text{ GeV} \leq m_h \leq 126 \text{ GeV}$.

Therefore, to have the possibility for some reduction of Y_b , we also consider the parameter space with values of M_A not too large (the quasi-decoupling regime), such that Y_b can be reduced to be below its SM value. At the same time the M_A values should be large enough such that $M_h \approx 125 \text{ GeV}$ is possible.

The results of our scan are presented in figure 2 where different values of $\kappa_{b\bar{b}}$ are plotted in the (M_A, μ) and $(A_t, \tan \beta)$ plane. From figure 2 one can see that large radiative SUSY corrections affecting Y_b indeed are correlated to small values of M_A and large values of μ (left frame) as well as with large values of $\tan \beta$ (right frame). These results are very consistent with eq. (3.8) which tells us that indeed large values of Δm_b can be achieved with large values of μ and/or $\tan \beta$. At the same time, lower values of M_A lead to the alteration of Y_b at tree-level: one can see that even for $M_A \simeq 500 \text{ GeV}$, as $\kappa_{b\bar{b}} < 0.5$ can be reached for sufficiently large values of $\tan \beta$ and μ . It is also worth mentioning that no obvious correlation of Δm_b with values of A_t can be seen in figure 2 since we require $M_h = 125 \pm 1 \text{ GeV}$, and this drives in turn the value of A_t to be around $\sqrt{6} M_{\text{SUSY}}$, i.e. near the maximal mixing scenario. Thus $A_t I(m_{t_1}^2, m_{t_2}^2, |\mu|^2) \approx \sqrt{6} M_{\text{SUSY}} I(m_{t_1}^2, m_{t_2}^2, |\mu|^2)$ which can be shown to decrease for large M_{SUSY} , limiting its maximum contribution to Δm_b .

3.2 Stop quark effects

As previously discussed, since $\frac{F_1}{F_0} \approx -20$, in order for stops to have a significant effect on $(h \rightarrow \gamma\gamma)$, $\hat{g}_{h\tilde{t}_1\tilde{t}_1}$ is required to be very large. Furthermore, a positive $\hat{g}_{h\tilde{t}_1\tilde{t}_1}$ coupling will decrease $\kappa_{\gamma\gamma}$ whilst a negative coupling will increase $\kappa_{\gamma\gamma}$.

In the decoupling limit, the Higgs coupling to the lightest stop is given by [10]

$$\hat{g}_{h\tilde{t}_1\tilde{t}_1} = \frac{1}{2} \cos 2\beta \left[\cos^2 \theta_t - \frac{4}{3} \sin^2 \theta_W \cos 2\theta_t \right] + \frac{m_t^2}{M_Z^2} + \frac{1}{2} \sin 2\theta_t \frac{m_t X_t}{M_Z^2}, \quad (3.12)$$

where $\theta_{\tilde{t}}$ is the stop mixing angle defined by

$$\sin 2\theta_t = \frac{2m_t X_t}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \quad (3.13)$$

and X_t is given in terms of the the Higgs-stop trilinear coupling as $X_t = A_t - \mu \cot \beta$.

The first term in the equation is small compared to $\frac{m_{\tilde{t}}^2}{M_Z^2}$ and so can be largely ignored.

When X_t is also small, then $\hat{g}_{h\tilde{t}_1\tilde{t}_1} \simeq \frac{m_{\tilde{t}}^2}{M_Z^2} > 0$ will lead to a decrease of $k_{\gamma\gamma}$. For large X_t , if $m_{\tilde{t}_1} < m_{\tilde{t}_2}$, it can be shown that $\sin 2\theta_{\tilde{t}} \simeq -1$ and the Higgs coupling to the lightest stop is strongly enhanced and negative. However, since $m_h \approx 125$ GeV, the scenario with light stops requires that the Higgs mixing should be near maximal, i.e., $X_t \approx \sqrt{6}M_{\text{SUSY}}$, where $M_{\text{SUSY}} = \frac{1}{2}(m_{\tilde{t}_1} + m_{\tilde{t}_2})$. Hence, we are not free to consider very large values of X_t as an independent parameter. In this case, one has

$$\hat{g}_{h\tilde{t}_1\tilde{t}_1} \sim \frac{m_{\tilde{t}}^2}{M_Z^2} + \frac{3}{2} \frac{m_{\tilde{t}}^2}{M_Z^2} \frac{(m_{\tilde{t}_1} + m_{\tilde{t}_2})^2}{(m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2)}. \quad (3.14)$$

Thus, if $m_{\tilde{t}_2}^2 \approx m_{\tilde{t}_1}^2$, it is possible to get a very large Higgs coupling to stops. However, with a light stop, such that $m_{\tilde{t}_1}^2 \ll m_{\tilde{t}_2}^2$, one finds

$$\hat{g}_{h\tilde{t}_1\tilde{t}_1} \rightarrow \frac{m_{\tilde{t}}^2}{M_Z^2} - \frac{3}{2} \frac{m_{\tilde{t}}^2}{M_Z^2} = -\frac{1}{2} \frac{m_{\tilde{t}}^2}{M_Z^2}. \quad (3.15)$$

Therefore $\hat{g}_{h\tilde{t}_1\tilde{t}_1}$ is both negative (making the overall stop loop contribution of the same sign as the W loop), thereby increasing $k_{\gamma\gamma}$, and fixed, which limits the overall contribution to $(h \rightarrow \gamma\gamma)$ of a stop loop of a particular mass. Small deviations from this prediction should be expected as in practice we are only requiring *near* maximal mixing.

This is illustrated in figure 3(a) where we present results for $\kappa_{\gamma\gamma}$ as a function of the lightest stop mass, $m_{\tilde{t}_1}$, where $124 \text{ GeV} < m_h < 126 \text{ GeV}$, for the scan described in section 2. Together with figure 3(b) which presents $\kappa_{\gamma\gamma}$ versus X_t/M_{SUSY} as well as m_h versus X_t/M_{SUSY} , these two figures provide a clear illustration of the argument discussed above: the effect of the stop is limited because of the correlation between $\hat{g}_{h\tilde{t}_1\tilde{t}_1}$ and the Higgs mass. As can be seen from figure 3(a), even $m_{\tilde{t}_1} \sim 120$ GeV would lead to a modest increase of $\kappa_{\gamma\gamma} \approx 1.2$. At the same time, in figure 3(b) which presents $\kappa_{\gamma\gamma}$, κ_{gg} and m_h as functions of $\frac{X_t}{M_{\text{SUSY}}}$, we can see that the effect of light stops on $\kappa_{\gamma\gamma}$ and κ_{gg} could be much larger if m_h was not limited to be in the 124–126 GeV mass window: outside of this window $\kappa_{\gamma\gamma}$ could be as large as 1.8 for a stop quark mass of about 120 GeV, however the majority of points with $X_t/M_{\text{SUSY}} > 3$ do not pass the colour breaking minima conditions discussed in section 2, limiting the maximum $\kappa_{\gamma\gamma}$ to around 1.5.

In this figure it is clear that, in order to get $m_h \approx 125$ GeV, X_t/M_{SUSY} has to be near its maximal mixing value of $\sqrt{6} \approx 2.4$. In this region there is little variation in $k_{\gamma\gamma}$ and we are limited to $0.9 \lesssim k_{\gamma\gamma} \lesssim 1.2$.

Let us consider the overall effect of light stops on $\mu_{ggF,\gamma\gamma} = k_{gg} \times k_{\gamma\gamma} \times k_h^{-1}$ via its effects on $k_{\gamma\gamma}$ and k_{gg} in the parameter space where the total width is close to the SM one. From figure 3(b) we would expect that, in general, either $k_{\gamma\gamma}$ is increased with a relatively

Figure 3. Left: $\kappa_{\gamma\gamma}$ (black) and κ_{gg} (green) as a function of lightest stop mass for $124 \text{ GeV} < m_h < 126 \text{ GeV}$. (b) $\kappa_{\gamma\gamma}$ (black), κ_{gg} (green) and m_h (red) as functions of $\frac{X_t}{M_{\text{SUSY}}}$ for $120 \text{ GeV} \leq m_{\tilde{t}_1} \leq 150 \text{ GeV}$. Cuts have been applied such that only points with a Higgs mass within 2 GeV of the maximum value for each value of $\frac{X_t}{M_{\text{SUSY}}}$ are kept. The pink-shaded window indicates the $X_t/M_{\text{SUSY}} > 3$ region, where the majority of points do not pass the colour breaking minima conditions. To isolate the influence of light stops, the following cuts are also applied to both plots: $m_{H^\pm}, m_{\chi_{1,2}^\pm}, m_{\tilde{\tau}_{1,2}}, m_{\tilde{b}_{1,2}}, m_{\tilde{t}_2} > 300 \text{ GeV}$.

larger decrease in k_{gg} , causing an overall decrease in $\mu_{ggF,\gamma\gamma}$, or $k_{\gamma\gamma}$ is decreased with a relatively larger increase in k_{gg} , causing an overall increase in $\mu_{ggF,\gamma\gamma}$. This is demonstrated in figure 4(a), where we see that (other than for a few points very near $\mu_{ggF,\gamma\gamma} = 1$ where other factors such as small changes in the total width play a role) we have $\mu_{ggF,\gamma\gamma} > 1$ when $k_{gg} > 1$ (red) and vice versa (black). This means that if the total width of the Higgs boson is unchanged, then stop loops alone can produce a universal increase in all decay channels ($\mu_{ggF,Y} > 1$) via increasing the ggF production channel but will not produce an isolated increase in $(h \rightarrow \gamma\gamma)$, as this will always be cancelled by a relatively larger decrease in ggF production.

We are naturally lead to consider the possibility of counteracting the effect of a reduced κ_{gg} caused by light stops by reducing $\Gamma_{b\bar{b}}$ as discussed in section 3.1.3. This would mean that when the stop coupling is negative, producing an increase in $k_{\gamma\gamma}$ and bigger relative decrease of κ_{gg} , the BRs in all channels other than $b\bar{b}$ can be increased such that the overall value for $\mu_{ggF,Y}$ remains ≈ 1 . In this scenario, $\mu_{\text{VBF},\gamma\gamma} > \mu_{ggF,\gamma\gamma}$ as the VBF channel will be increased by both $k_{\gamma\gamma} > 1$ and the increased BR to photons from the reduced total width, without the reduced production rate of the ggF channel. This is demonstrated in figure 4(b,c) where the effects of light stops and reduced $\Gamma_{b\bar{b}}$ (via a reduction in the bottom Yukawa coupling) are combined together and the resulting $\mu_{\text{VBF},\gamma\gamma}$ and $\mu_{ggF,\gamma\gamma}$ values along with current best fit CMS and ATLAS data are plotted. One can see in figure 4(b) that the smaller the $\kappa_{b\bar{b}}$ values, the larger the *universal* $\mu_{\text{VBF},\gamma\gamma}$ and $\mu_{ggF,\gamma\gamma}$ alterations it will

Figure 4. (a) $\mu_{ggF,\gamma\gamma}$ vs lightest stop mass for $\kappa_{gg} > 1$ (red) and $\kappa_{gg} \leq 1$ (black). We have cut for $0.98 \leq \kappa_{bb} \leq 1.02$ to remove the possible effect of a reduced $\Gamma_{h\bar{b}b}$. (b) Each point of the scan with $120 \text{ GeV} \leq m_{\tilde{t}_1} \leq 300 \text{ GeV}$ is plotted on the (μ_{VBF}, μ_{ggF}) plane, with colours to indicate different values for κ_{bb} , (c) different $m_{\tilde{t}_1}$ masses. The results from ATLAS (purple circle) and CMS (yellow diamond) are indicated for comparison. In all the plots, $124 \text{ GeV} \leq m_h \leq 126 \text{ GeV}$, and to isolate the influence of light stops the following cuts are also applied: $m_{H^\pm}, m_{\chi_{1,2}^\pm}, m_{\tilde{\tau}_{1,2}}, m_{\tilde{b}_{1,2}}, m_{\tilde{t}_2} > 300 \text{ GeV}$.

cause, while figure 4(c) clearly demonstrates how decreased stop quark masses lead to an increase of the *non-universal* alteration of these couplings, which can be expressed through the $\mu_{VBF,\gamma\gamma}/\mu_{ggF,\gamma\gamma}$ ratio.

In this scenario, the same situation takes place for all other decay channels with the exception of the decay to bottoms, ($\mu_{VBF,WW/ZZ/\tau\tau/\gamma\gamma} > \mu_{ggF,WW/ZZ/\tau\tau/\gamma\gamma}$), as will be discussed further in section 3.5. Furthermore, in this region, the di-photon decay channel can be increased by a factor of up to 1.2 relative to the other decay channels.

Of note, the area of parameter space with light stops and a Higgs mass of $\approx 125 \text{ GeV}$ is relatively small, because a heavy M_{SUSY} is preferred to give large logarithmic parts to the radiative corrections to the Higgs Mass. The scenario where $M_{U3} \sim M_{Q3} \gtrsim 300 \text{ GeV}$ requires fine-tuning of the stop mixing parameter X_t in order to achieve a lightest stop with mass $\leq 300 \text{ GeV}$. However, as X_t is fixed by the near maximal mixing requirement ($X_t \approx \sqrt{6}M_{\text{SUSY}}$), this is not possible. Hence, the area of parameter space with a $\approx 125 \text{ GeV}$ lightest Higgs mass and light stops (with mass $\leq 300 \text{ GeV}$) is where $M_{U3} \ll M_{Q3}$, generally with $M_{U3} \leq 300 \text{ GeV}$ and $M_{Q3} \gtrsim 2 \text{ TeV}$. (In this region it is easy to show that $m_{\tilde{t}_1} \approx M_{U3}$ and $m_{\tilde{t}_2} \approx M_{Q3}$.) This explains the reason for choosing the reduced range of M_{U3} described in section 2 for the additional scan. The relationship between M_{U3} , M_{Q3} and the lightest stop mass is shown in figure 5, exemplifying a strong correlation between $m_{\tilde{t}_1}$ and M_{U3} as discussed.

In table 2, we give three different benchmark points for scenarios where light stops give rise to $\frac{\mu_{VBF}}{\mu_{ggF}} > 1$, where we have also included a value for the minimum fine-tuning for each of the benchmark points.

Figure 5. Different values for $m_{\tilde{t}_1}$ in the M_{U3} versus M_{Q3} plane. We have required $124 \text{ GeV} \leq m_h \leq 126 \text{ GeV}$.

Our fine-tuning parameter is based on the electroweak fine-tuning parameter (see e.g. [66] for details). This value is derived by noting that the minimisation condition for the Higgs potential gives rise to the equation for the Z -boson mass,

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2 \quad (3.16)$$

where Σ_u^u and Σ_d^d are the radiative corrections to $m_{H_u}^2$ and $m_{H_d}^2$. The electroweak fine-tuning parameter is then defined as

$$\Delta_{\text{EW}} \equiv \max_i(C_i)/(M_Z^2/2) \quad (3.17)$$

where $C_{H_u} = |-m_{H_u}^2 \tan^2 \beta / (\tan^2 \beta - 1)|$, with analogous definitions for C_{H_d} , C_μ , $C_{\Sigma_u^u}$ and $C_{\Sigma_d^d}$. If $\tan \beta$ is moderate or large, we have

$$\frac{M_Z^2}{2} \approx -(m_{H_u}^2 + \Sigma_u^u) - \mu^2. \quad (3.18)$$

Taking into account that Σ_u^u is not defined if our starting point is the theory at the EW scale (rather than the GUT scale) the measure of fine-tuning

$$\Delta \equiv |\mu^2|/(M_Z^2/2) \quad (3.19)$$

gives a *minimum* value for Δ_{EW} , which could be larger if there is a large cancellation between $m_{H_u}^2$ and Σ_u^u as discussed by Baer et al. in [66]. Keeping this in mind we will be using this definition of fine-tuning in our paper.

We see that for Benchmark points 1 and 3, $\Delta^{-1} \sim 2\text{--}5\%$, as there is no requirement for a large μ . However Benchmark 2 has a reduced k_{bb} which requires a large Δm_b and hence a large μ , leading to a larger minimum fine-tuning, with $\Delta^{-1} \sim 0.1\%$.

Parameter	Benchmark 1	Benchmark 2	Benchmark 3
$\tan \beta$	37	48	44
μ	300 GeV	2 TeV	400 GeV
$M_{H^\pm}$	1.7 TeV	1 TeV	750 GeV
M_{Q3}	2.5 TeV	2.5 TeV	1.3 TeV
M_{U3}	165 GeV	230 GeV	320 GeV
M_{D3}	11 TeV	12 TeV	7 TeV
M_{L3}	4 TeV	3 TeV	2 TeV
M_{E3}	1.2 TeV	500 GeV	5 TeV
M_3	1.9 TeV	3.2 TeV	2 TeV
M_2	3 TeV	3 TeV	3 TeV
M_1	125 GeV	172 GeV	250 GeV
A_t	3.1 TeV	3.6 TeV	2.1 TeV
A_b	5.5 TeV	100 GeV	7 TeV
A_τ	500 GeV	0 GeV	2.5 TeV
$m_{\tilde{t}_1}$	125 GeV	177 GeV	254 GeV
$m_{\tilde{\chi}_1^0}$	121 GeV	172 GeV	245 GeV
m_h	124.1 GeV	124.0 GeV	124.2 GeV
$\frac{\mu_{\text{VBF}, \gamma\gamma}}{\mu_{ggF, \gamma\gamma}}$	$\frac{1.11}{0.78} = 1.42$	$\frac{1.65}{1.16} = 1.42$	$\frac{1.08}{0.80} = 1.35$
κ_{gg}	0.71	0.70	0.74
$\kappa_{\gamma\gamma}$	1.10	1.10	1.08
κ_{bb}	1.01	0.55	1.04
κ_h	0.99	0.67	1.01
$\mu_{ggF, bb}$	0.72	0.58	0.76
Δ^{-1}	4.6%	0.1%	2.6%

Table 2. Benchmark points with light stops and $\frac{\mu_{\text{VBF}}}{\mu_{ggF}} > 1$.

We should also mention here that the light stop scenario has been discussed recently in connection to EWBG [67, 68]. The latter requires $A_t \lesssim M_{Q3}/2$ (or $X_t/M_{\text{SUSY}} \lesssim \frac{1}{\sqrt{2}}$) in order to achieve a strong phase transition and therefore is not realised in the maximal mixing scenario which we consider in our paper. Remarkably, for these values of X_t/M_{SUSY} , the 125 GeV Higgs mass can be only achieved for extremely large values of $M_{Q3} \simeq 10^6$ TeV, as shown in [68]. At the same time, $X_t/M_{\text{SUSY}} \lesssim \frac{1}{\sqrt{2}}$ leads to $\hat{g}_{h\tilde{t}_1\tilde{t}_1} > 0$ and therefore to a constructive interference of the light stops inside ggF production. It was suggested in [68] that the overall enhancement for ggF production coming from the light stop can be compensated by a significant invisible Higgs boson decay into light neutralinos.

We would also like to note that the scenario with an altered Y_b coupling that we consider in this paper suggests an alternative solution to the problem of how to compensate the enhancement of ggF production due to light stops. Analogously to the parameter space region where Y_b is decreased, there is another where Y_b is increased, which is realised in the $\mu < 0$ region. In this case, the enhancement of ggF production is compensated by

the respective decrease of the $\gamma\gamma/ZZ/WW/\tau\tau$ decay rates while the $\text{BR}(h \rightarrow b\bar{b})$ will be increased. Since, at the moment, the LHC is not quite sensitive to the $h \rightarrow b\bar{b}$ signature, this scenario is perfectly viable.

3.3 Sbottom quark effects

Similarly to stops, light sbottoms loops may also alter Higgs production via ggF and decay to di-photons. However, there are some important differences between the sbottom loop contribution and the stop loops.

In the decoupling limit, the Higgs coupling to sbottoms is given by

$$\hat{g}_{h\tilde{b}_1\tilde{b}_1} = \cos 2\beta \left(-\frac{1}{2} \cos^2 \theta_{\tilde{b}} + \frac{1}{3} \sin^2 \theta_W \cos 2\theta_{\tilde{b}} \right) + \frac{m_b^2}{M_Z^2} + \frac{m_b X_b}{2M_Z^2} \sin 2\theta_{\tilde{b}}, \quad (3.20)$$

where $\theta_{\tilde{b}}$ is the sbottom mixing angle defined by

$$\sin 2\theta_{\tilde{b}} = \frac{2m_b X_b}{m_{\tilde{b}_1}^2 - m_{\tilde{b}_2}^2} \quad (3.21)$$

and $X_b = A_b - \mu \tan \beta$.

The first major difference with respect to the stop case is that this coupling does not have any dependence on X_t and, hence, is not constrained by the requirement of $m_h \approx 125 \text{ GeV}$. In particular, when $m_{\tilde{b}_1} < m_{\tilde{b}_2}$ with a large positive μ and $\tan \beta$, leading to a large negative X_b , it can be shown that $\sin 2\theta_{\tilde{b}} \sim 1$. The last term in eq. (3.20) therefore dominates, giving

$$\hat{g}_{h\tilde{b}_1\tilde{b}_1} \simeq \frac{m_b X_b}{2M_Z^2} \quad (3.22)$$

and leading to a large negative coupling due to the negative X_b . As the Higgs-sbottom coupling ultimately depends on X_b^2 , via the $\sin 2\theta_{\tilde{b}}$ term, it is also possible to get a large negative coupling if μ is large and negative such that X_b is large and positive. However, as we are interested in the parameter space where Y_b has the possibility of being small, which requires a positive μ (see section 3.1), we have only considered positive μ .

The second important difference with respect to the stop case is that $N_{c,b}Q_b^2 = 1/3$ versus $N_{c,t}Q_t^2 = 4/3$ for stops. This will not affect gluon fusion, but means that the sbottom mass will need to be $\frac{1}{2}$ that of a stop mass with the same coupling strength to Higgs bosons to produce the same alteration in decay to photons.

The result of the two factors discussed above is that, firstly, due to the opposing effects of the sbottom coupling having a larger maximum magnitude compared to stops, but the sbottom loop effects of decay to di-photons being suppressed by a factor of $\frac{Q_t^2}{Q_b^2}$ compared to stops, the relative effects of sbottom loops on $\kappa_{\gamma\gamma}$ compared to stop loops is difficult to predict. Secondly, the maximum effect of sbottom loops on gluon fusion can be larger than that of a stop with the same mass, because the coupling isn't constrained by the Higgs mass and can become larger in magnitude than the stop coupling, while the loop contribution isn't constrained by a charge factor as is the case for di-photon decay.

Both of these effects can be observed in figure 6(a). We see that the largest possible increase in $\kappa_{\gamma\gamma}$ (black) for a given sbottom mass is smaller than that for a stop of the same

Figure 6. (a) $\kappa_{\gamma\gamma}$ (black) and κ_{gg} (green) as a function of lightest sbottom mass for $124 \text{ GeV} < m_h < 126 \text{ GeV}$. (b) $\kappa_{\gamma\gamma}$ (black) and κ_{gg} (green) as functions of $\frac{X_b}{(m_{\tilde{b}_1}^2 + m_{\tilde{b}_2}^2)^{1/2}}$ for $120 \text{ GeV} < m_{\tilde{b}_1} \leq 150 \text{ GeV}$. To isolate the influence of light sbottoms, the following cuts are also applied: $m_{H^\pm}, m_{\chi_{1,2}^\pm}, m_{\tilde{t}_{1,2}}, m_{\tilde{\tau}_{1,2}}, m_{\tilde{b}_2} > 300 \text{ GeV}$.

mass, and only very light sbottoms $\simeq 80 \text{ GeV}$ are able to produce $\kappa_{\gamma\gamma} \approx 1.2$ (compare to $m_{\tilde{t}_1} \approx 120 \text{ GeV}$). Also, as expected, κ_{gg} (green) has a larger reduction for sbottoms compared to stops of similar mass, with κ_{gg} as low as 0.7, for $m_{\tilde{b}_1} \approx 250 \text{ GeV}$.

Figure 6(b) shows how $\kappa_{\gamma\gamma}$ (black) and κ_{gg} (green) depend on $\sqrt{\frac{X_b}{m_{\tilde{b}_1}^2 + m_{\tilde{b}_2}^2}}$ for $120 \text{ GeV} < m_{\tilde{b}_1} < 150 \text{ GeV}$, confirming that the largest deviations from the SM occur for large and negative X_b , and that the effect on κ_{gg} is much larger than for $\kappa_{\gamma\gamma}$.

The combined effect of the sbottom loops can be seen in figure 7(a), where the lightest sbottom mass is plotted against $\mu_{ggF,\gamma\gamma}$. We see that for the majority of parameter space, $\mu_{ggF,\gamma\gamma}$ is suppressed, other than a small region where it is increased due an increased κ_{gg} . This small region of increased κ_{gg} occurs for very small values of X_b where the final term of eq. (3.20) does not dominate and the coupling is small and positive.

If we consider the possibility of counteracting the effect of a reduced κ_{gg} by reducing $\Gamma_{b\bar{b}}$ as we did for the stops, we find that we would expect sbottom loops to have a similar effect to stop loops in the $(\mu_{\text{VBF},\gamma\gamma}, \mu_{ggF+ttH})$ plane. As in the stop case, VBF production channels will be unaffected by the gluon fusion rate, but the decays to all particles (other than sbottoms) will still be increased by the reduction in $\Gamma_{b\bar{b}}$, such that $\mu_{\text{VBF},\gamma\gamma} > \mu_{ggF,\gamma\gamma}$.

This is demonstrated in figure 7(b), which is analogous to figure 4(b) for stops, where we have plotted $\mu_{\text{VBF},\gamma\gamma}$ versus $\mu_{ggF,\gamma\gamma}$ for different values of $\kappa_{b\bar{b}}$, for $120 \text{ GeV} < m_{\tilde{b}_1} < 300 \text{ GeV}$. In the case of sbottoms, as the arrows indicate, their main effect is to reduce κ_{gg} , reducing $\mu_{ggF,\gamma\gamma}$, with a much smaller effect on $\kappa_{\gamma\gamma}$, producing only a small increase in

Figure 7. (a) $\mu_{ggF,\gamma\gamma}$ vs lightest sbottom mass for $\kappa_{gg} > 1$ (red) and $\kappa_{gg} \leq 1$ (black). We have cut for $0.98 \leq \kappa_{bb} \leq 1.02$ to remove the possible effect of a reduced $\Gamma_{hb\bar{b}}$. (b) Each point of the scan with $120 \text{ GeV} \leq m_{\tilde{b}_1} \leq 300 \text{ GeV}$ is plotted on the (μ_{VBF}, μ_{ggF}) plane, with colours to indicate different values for κ_{bb} , (c) different $m_{\tilde{b}_1}$ masses. The results from ATLAS (purple circle) and CMS (yellow diamond) are indicated for comparison. In all the plots, $124 \text{ GeV} \leq m_h \leq 126 \text{ GeV}$, and to isolate the influence of light sbottoms the following cuts are also applied: $m_{H^\pm}, m_{\chi_{1,2}^\pm}, m_{\tilde{t}_{1,2}}, m_{\tilde{\tau}_{1,2}}, m_{\tilde{b}_2} > 300 \text{ GeV}$.

$\mu_{VBF,\gamma\gamma}$. The reduced Yukawa coupling to bottoms then reduces the total width, causing a universal increase in $\mu_{\gamma\gamma}$ irrespective of the production channel. Overall, we see that, in this situation, light sbottoms can produce quite large non-universal alterations, which can be measured by the $\frac{\mu_{VBF,\gamma\gamma}}{\mu_{ggF,\gamma\gamma}}$ ratio which can be even larger than in the light stop scenario. Figure 7(c) is similar to figure 7(b), but with the colours indicating the sbottom mass in each case. We see that the largest effects are produced by the lightest sbottoms, as expected, but that a significant effect giving $\frac{\mu_{VBF,\gamma\gamma}}{\mu_{ggF,\gamma\gamma}} \sim 1.2$ is still possible for sbottoms as heavy as $250 \text{ GeV} \leq m_{\tilde{b}_1} \leq 300 \text{ GeV}$.

3.4 Stau effects

In addition to light stops and sbottoms, the lightest stau may give important contributions that in particular could enhance $\kappa_{\gamma\gamma}$. For staus, $N_c Q^2 = 1$, a factor of 3 larger than sbottoms, and since the Higgs-stau coupling like the Higgs-sbottm coupling also does not depend on X_t , and hence is not constrained by the Higgs mass, light stau effects on $\Gamma(h \rightarrow \gamma\gamma)$ could be more significant than sbottom effects, with the caveat of a different (running) bottom mass versus the tau mass.

The Higgs coupling to the lightest stau, normalised by $v/\sqrt{2} = M_W/g$, with v the SM Higgs VEV, is given by

$$\hat{g}_{h\tilde{\tau}_1\tilde{\tau}_1} = \cos 2\beta \left(-\frac{1}{2} \cos^2 \theta_{\tilde{\tau}} + \sin^2 \theta_W \cos 2\theta_{\tilde{\tau}} \right) + \frac{m_\tau^2}{M_Z^2} + \frac{m_\tau X_\tau}{2M_Z^2} \sin 2\theta_{\tilde{\tau}} \quad (3.23)$$

with $X_\tau = A_\tau - \mu \tan \beta$.

Figure 8. (a) $\kappa_{\gamma\gamma}$ (black) and κ_{gg} (green) as a function of lightest stau mass for $124 \text{ GeV} < m_h < 126 \text{ GeV}$. (b) $\kappa_{\gamma\gamma}$ (black) and κ_{gg} (green) as functions of $\frac{X_\tau}{(M_{\tilde{\tau}_1}^2 + M_{\tilde{\tau}_2}^2)}$ for $120 \text{ GeV} \leq m_{\tilde{\tau}_1} \leq 140 \text{ GeV}$. To isolate the influence of light staus, the following cuts are also applied: $m_{H^\pm}, m_{\chi_{1,2}^\pm}, m_{\tilde{t}_{1,2}}, m_{\tilde{b}_{1,2}}, m_{\tilde{\tau}_2} > 300 \text{ GeV}$.

Similarly to sbottoms, for a large positive μ , with large $\tan \beta$, X_τ is large and negative, and we find that

$$\hat{g}_{h\tilde{\tau}_1\tilde{\tau}_1} \simeq \frac{m_\tau X_\tau}{2M_Z^2}, \quad (3.24)$$

which is large and negative. Thus the stau contribution may enhance $\Gamma(h \rightarrow \gamma\gamma)$ in a large $\tan \beta$ scenario with large and positive μ . (As in the sbottom case, a large negative μ would also give rise to a large negative coupling, but we only consider positive μ , as required such that Y_b may be reduced.) As intimated, since $N_c Q^2$ is 3 times larger for the stau than the sbottom, the minimum mass at which its contribution to $\kappa_{\gamma\gamma}$ can become large is approximately a factor of $\sqrt{3}$ times heavier than for the sbottom.

This is demonstrated in figure 8(a), where $\kappa_{\gamma\gamma}$ (black) is plotted against the stau mass, indeed showing that we can have $\kappa_{\gamma\gamma} > 1.2$ when $m_\tau \lesssim 180 \text{ GeV}$. It also shows that light staus have no effect on κ_{gg} as expected. (The points with a slight reduction in κ_{gg} have sbottoms or stop masses $\sim 300 \text{ GeV}$, just above the mass cut applied for these particles.) In figure 8(b), $\kappa_{\gamma\gamma}$ and κ_{gg} are plotted against $\frac{X_\tau}{\sqrt{(M_{\tilde{\tau}_1}^2 + M_{\tilde{\tau}_2}^2)}}$, showing that as for the sbottom, the coupling becomes largest for large and negative X_τ .

As staus are colourless and do not affect the gluon-gluon fusion production channel, $\mu_{ggF,\gamma\gamma}$ follows a very similar pattern as $\kappa_{\gamma\gamma}$. This is illustrated in figure 9(a) where we see that for $m_{\tilde{\tau}_1} \lesssim 180 \text{ GeV}$, the value of $\mu_{ggF,\gamma\gamma}$ can become > 1.2 .

In figure 9(b,c), we see that the effect of the light staus on the $(\mu_{\text{VBF+VH}}, \mu_{ggF+ttH})$ plane is as expected, causing a universal increase in decay to di-photons irrespective of

Figure 9. (a) $\mu_{ggF,\gamma\gamma}$ vs lightest stau mass. We have cut for $0.98 \leq \kappa_{bb} \leq 1.02$ to remove the possible effect of a reduced $\Gamma_{hb\bar{b}}$. (b) Each point of the scan with $120 \text{ GeV} \leq m_{\tilde{\tau}_1} \leq 300 \text{ GeV}$ is plotted on the (μ_{VBF}, μ_{ggF}) plane, with colours to indicate different values for κ_{bb} , (c) different $m_{\tilde{\tau}_1}$ masses. The results from ATLAS (purple circle) and CMS (yellow diamond) are indicated for comparison. In all the plots, $124 \text{ GeV} \leq m_h \leq 126 \text{ GeV}$, and to isolate the influence of light staus the following cuts are also applied: $m_{H^\pm}, m_{\chi_{1,2}^\pm}, m_{\tilde{t}_{1,2}}, m_{\tilde{b}_{1,2}}, m_{\tilde{\tau}_2} > 300 \text{ GeV}$.

production channel, magnifying also universal effects which may be caused by a reduction in $\Gamma_{hb\bar{b}}$.

3.5 Combined effect and fit of the LHC data

In figure 10 we present results for μ_{VBF} versus μ_{ggF} for the $\gamma\gamma$, WW , ZZ , $\tau\tau$ and $b\bar{b}$ decay channels in the (μ_{VBF}, μ_{ggF}) plane, where we have included all points from our scan for which any or all of the scenarios discussed in the previous subsections are realised. We see that, for each final state, the majority of parameter space has $\mu_{VBF} > \mu_{ggF}$, and comparing with experimental measurements, we see that 6 out of 8 measurements have $\mu_{VBF} > \mu_{ggF}$ for their best fit values. Therefore one can expect that the MSSM will provide a better fit to the data and, in general, that the light stop and sbottom scenarios would be able to explain a non-universal alteration of $\mu_{VBF} > \mu_{ggF}$, if this is confirmed at the upgraded LHC starting in 2015. In figure 10 we have also stratified by shading according to the values of the fine-tuning parameter Δ , as described in section 3.2. We see that the points with a large universal increase in μ_{ggF} and μ_{VBF} have a larger fine tuning in general. This is expected, as for these points μ , on which Δ depends, is required to be large to reduce Y_b as discussed in section 3.1.

To quantify how well the scenarios we have discussed fit current LHC data, we have calculated the χ^2 for each scenario and compared to the best fit values for μ_{ggF} and μ_{VBF} in figure 1. For each collaboration (ATLAS, CMS) the systematic errors on the values of μ_{ggF} and μ_{VBF} for a single decay mode are correlated. To take this correlation into account, we actually calculate a “profiled log likelihood ratio” test statistics. However, under the assumption that the data is distributed as a multivariate Gaussian (valid to a good approximation), this reduces to a χ^2 statistics with a non-diagonal covariance matrix.

Figure 10. μ_{VBF} vs μ_{ggF} for the di-photon, WW , ZZ , $\tau\tau$ and $b\bar{b}$ decay channels where the lightest stop and/or lightest stau and/or lightest sbottom has a mass between 120 GeV–300 GeV. ATLAS (circle) and CMS (square) best fit results for each channel are also plotted. The 68% Confidence Level (CL) for the experimental results are included. ATLAS results were not available for the $b\bar{b}$ and $\tau\tau$ channels. Colour gradients denote different values of the fine-tuning parameter $\Delta^{-1} \times 100$ as described in subsection 3.2.

This is discussed fully in [69]. There are 6 degrees of freedom from the ATLAS data and 10 from the CMS data, giving 16 degrees of freedom overall (3 channels for ATLAS ($\gamma\gamma$, WW and ZZ) and 5 from CMS ($\gamma\gamma$, WW , ZZ , $\tau\tau$, $b\bar{b}$), each with ggF and VBF channels). The regions of interest for which a χ^2 was calculated were defined as; 1) light stops only, 2) light sbottoms only, 3) light staus only, 4) lights stops and/or sbottoms and/or staus. In each case a “light” mass was defined as between 120 and 300 GeV.

For each case, we have calculated the χ^2 for each point in the parameter space from our scan that matched the aforementioned particle mass criteria. The results are presented in figure 11 as the χ^2 per degree of freedom (χ^2/N_{DOF}), when compared to (a) just the ATLAS results, (b) just the CMS results, (c) both ATLAS and CMS results.

First of all, one can see that the SM already fits the data well, the χ^2/N_{DOF} is about 1 for ATLAS (figure 11(a)) and is about 0.6 for CMS (figure 11(b)), while for the ATLAS+CMS combination we have got $\chi^2/N_{\text{DOF}} \sim 0.75$ (figure 11(c)). One should note that the χ^2/N_{DOF} is lower for CMS, mainly due to the best fit point for $h \rightarrow ZZ$ being very close to the SM value, and for $h \rightarrow b\bar{b}$ being reasonably close to the SM with very large

Figure 11. χ^2 results per degree of freedom for different regions in parameter space compared to (a) ATLAS data, (b) CMS data, (c) combined ATLAS+CMS data. The width of each block is proportional to the number of points in each region of parameter space with each particular value of χ^2 . The light stop, sbottom and stau regions are defined as $120 \text{ GeV} \leq m_i \leq 300 \text{ GeV}$, where $m_i = m_{\tilde{t}_1}, m_{\tilde{b}_1}, m_{\tilde{\tau}_1}$ respectively. The SM fit to data is indicated by the green line for each plot.

error bars. It is hard to judge which scenario is preferred due to the large experimental errors, but one can see that the combined scenario as well as the scenario with light staus give the lowest value of χ^2/N_{DOF} .

4 Conclusions

In this paper we have explored the effect from light sfermions on the production and decay of the lightest Higgs boson within the MSSM culminating with a fit of the relevant parameter space to LHC data.

We have found that the scenario with light coloured sfermions, namely stops and sbottoms, has the potential to explain a non-universal alteration of the two most relevant Higgs production channels, i.e., $\mu_{\text{VBF}} \neq \mu_{ggF}$, and predicts $\frac{\mu_{\text{VBF}}}{\mu_{ggF}} > 1$ in all Higgs boson

decay channels in the majority of the parameter space. These light stop and light sbottom scenarios are realised in specific regions of the parameter space in terms of soft-breaking mass terms, namely where $M_{Q3} \gg M_{U3}$ and $M_{Q3} \gg M_{D3}$, respectively.

The specific feature of the scenario with a light stop is that $\hat{g}_{h\tilde{t}_1\tilde{t}_1}$ is negative (whenever one is near maximal stop mixing), which makes the overall stop loop contribution of the opposite sign as the top quark contribution and of same sign as the W loop. As a result, one obtains a decreased k_{gg} and an increased $k_{\gamma\gamma}$ couplings. It is important to notice that the relative decrease of k_{gg} is bigger than the relative increase of $k_{\gamma\gamma}$, so the overall effect from light stops per se would lead to a decrease of the Higgs production via gluon-gluon fusion decaying to di-photons ($\mu_{ggF,\gamma\gamma}$) as well as a reduction in μ_{ggF} compared to the SM for all decay channels ($\mu_{ggF}^{\text{SM}} = 1$ by definition). This scenario would be somewhat consistent with CMS data, where $\mu_{ggF} < 1$ for all decay channels.

However, this prediction is in tension with the ATLAS data where $\mu_{ggF} \approx 1.5$ for both the $\gamma\gamma$ and ZZ decay channels. Therefore, we also consider the scenario where we have both light stops and a suppressed $hb\bar{b}$ coupling. In this case, the reduced $h \rightarrow b\bar{b}$ partial width (and related κ_{bb} parameter) causes an enhancement of the BRs and hence signal strengths of the other decay channels, which can compensate for the reduced production via ggF . In this case, depending on the degree of suppression of the $hb\bar{b}$ coupling, the ggF signal strength in all channels can be increased, either to match the SM level, or greater, e.g., to $\mu_{ggF} \approx 1.5$, in order to be more consistent with the ATLAS data. The exceptions being $\mu_{ggF,\gamma\gamma}$, which can be slightly enhanced, and $\mu_{ggF,b\bar{b}}$, which would be reduced compared to the other channels. This reduction of the $hb\bar{b}$ coupling was achieved with a large μ (1–5 TeV), intermediate M_A (300–800 GeV) and intermediate-to-large $\tan\beta$ (20–50).

One should also note that, in the light stop scenario, $\hat{g}_{h\tilde{t}_1\tilde{t}_1}$ is fixed (in the maximal mixing scenario) to about $-\frac{1}{2}\frac{m_t^2}{M_{\tilde{Z}}^2}$, which limits the maximal contribution of the stop to production via ggF and to the $h \rightarrow \gamma\gamma$ decay. We have also found that the effect from light sbottoms on the gluon fusion rate can be potentially larger (since Higgs-sbottom-sbottom coupling is not correlated with the Higgs boson mass), which in its turn requires a bigger decrease for κ_{bb} to satisfy the experimental data. One can see that, in the light stop/sbottom scenarios, $\mu_{ggF,b\bar{b}}$ and $\mu_{\text{VBF},b\bar{b}}$ are predicted to be essentially below unity, especially the $\mu_{ggF,b\bar{b}}$ value, which is doubly suppressed both via ggF production (due to the negative interference from stop/sbottom loops) and from decay (due to κ_{bb} suppression). Therefore, in the future LHC runs, the measurement of $\mu_{ggF,b\bar{b}}$ and $\mu_{\text{VBF},b\bar{b}}$ is particularly important, as this will enable one to exploit an additional constraint in order to pin down possible MSSM effects in the Higgs sector.

In contrast, light staus were found to be able to only universally increase the signal strengths, irrespective of the production channel, generally complementing the effect of a reduced $hb\bar{b}$ coupling.

Furthermore, we showed that the non-universal solutions ($\mu_{ggF} \neq \mu_{\text{VBF}}$) had a fairly low minimum fine-tuning measure, as low as $\sim 5\%$, while in regions where a universal increase in signal strength ($\mu_{ggF} \sim \mu_{\text{VBF}} > 1$) is caused due to a suppressed Y_b , the fine-tuning was much larger due to the requirement of a large μ parameter.

Finally, we performed a χ^2 fit for these MSSM scenarios which showed that they all fit data better than the SM.

To conclude, we have found that the MSSM with light stops or sbottoms has a good potential to explain a non-universal alteration of the Higgs production rates in different channels as compared to the SM and that this can be complemented by the fact that a reduced Γ_h could increase the relevant signal strengths to be equal to or greater than the SM prediction.

As an outlook, we should mention the fact that, among the light squark solutions considered, the light stop one is also attractive from a cosmological point of view. In fact, the scenario where the neutralino (the LSP) is degenerate with the lightest stop in the 100–300 GeV range (to satisfy the experimental data on stop quark searches) predicts a plausibly low amount of DM (via the stop-neutralino co-annihilation channel). At the same time the light stop scenario can provide a crucial link to EWBG, specifically in case of very light stops. In this connection, we also suggest an alternative solution of compensating the enhancement of ggF production due to light stops (which takes place away from maximal mixing scenario), through an increase of Y_b and a respective decrease of the $\gamma\gamma/ZZ/WW/\tau\tau$ decay rates.

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